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A review on the economic dispatch and risk management considering wind power in the power market

Ren Boqiang, Jiang Chuanwen *

Department of Electrical Engineering, Shanghai Jiaotong University, Huashan Road 1954, Shanghai 200030, PR China

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ABSTRACT

With the rapid development of world economy, wind power has been given more and more consideration owing to its energy saving and environmental protection. But due to intermittency and unpredictability nature of wind power generation, many new problems come into being when infusing wind power into power network with conventional generators. Aiming at these difficulties, this paper presents a review on the historical research production of this theme. The models of economic dispatch schedule of wind power considering dissimilar actual condition, different optimized algorithms and risk management in the electric market are discussed and the future trend is prospected in this paper.

Contents

* Corresponding author. Tel.: +86 21 34205930; fax: +86 21 54747501.
E-mail address: jiangcw@sjtu.edu.cn (J. Chuanwen).

Abbreviations: HTG, hydro-thermal generation; WTG, wind turbine generation; ED, economic dispatch; CDED, constrained dynamic economic dispatch; WECS, wind energy conversion system; EES, electrical energy storage; AV, added value; DSM, direct search method; EP, evolutionary programming; SA, simulated annealing; PSO, particle swarm optimization; MOPSO, multi-objective particle swarm optimization; GA, genetic algorithm; IPP, independent power producer.

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Nomenclature

M	number of conventional power generators
N	number of wind-powered generators
k	scenario k
F_T	the expected social cost
P_i	active power from the ith conventional generator
μ	system security level
L	load value
C_i	cost function for the ith conventional generator
$C_{i,w}$	cost function for the ith wind-powered generator
$C_{p,w,i}$	penalty cost function
$C_{r,w,i}$	required reserve cost function
$C_g(\ )$	fixed running and startup costs of hydro-thermal generation
$C_r(\ )$	scheduling costs of tertiary reserve services during period
$w_{i,av}$	available wind power from the ith wind-powered generator
w_i	scheduled wind power from the ith wind-powered generator
$w_{i,r}$	rated wind power from the ith wind-powered generator
r_t^{up}	generation and voluntary demand-side up spinning reserves
r_t^{dn}	generation and voluntary demand-side down spinning reserves
$g_i(\ )$	vector of HTG outputs
$p_i(\ )$	probability value
$B_d(\ )$	demand benefits
$d_i(\ )$	forecast sequences
$l_i(\ )$	involuntary load shedding
v_i^T	vector of values of lost load
u_t	historical mean wind speed during period
σ_t	the simulated wind speed during period
v_t	the simulated wind speed during period
y_t	the time series value at time t
$P_{i,\min}$	minimum active power from the ith conventional generator
$P_{i,\max}$	maximum active power from the ith conventional generator

1. Introduction

With the rapid development of world economy, people have paid more attention to the consumption of fuel and protection of environment. As one of the most promising non-pollution renewable energy sources, the wind power, which is very different from the conventional energy sources, has been given more consideration by policies. Comparing with conventional generator, the wind turbine generator has the advantage of reducing the dependence on fossil fuels and the transmission losses, enhancing the independence and flexibility of large power grid.

Because the output of wind power depends on the wind speed which is related with climatological and micrometeorological parameters, wind behavior is quite distinct from conventional energy operation at their rated capacities. Due to the intermittency and unpredictability nature of wind power generation, which can influence the schedule of generation and control of frequency, the more scientific and reasonable theory should be researched to help wind power be used in power network in a large scale. So how to make reasonable long-term and short-term schedules and manage the uncertainty risk of wind power in the market including wind turbine generators is the main thesis of this paper. The economic dispatch (ED) of wind power should consider many factors, e.g. environmental damage cost and spinning reserves. Different factors determine different dispatch models and solution. Risk management of wind power in this paper does not include volatility of imbalance charge rates and market price which can be obtained or solved beforehand, but the stochastic characteristic cannot be eliminated at present.

This paper is organized as follows. Sections 2 and 3 present multifarious kinds of wind power models based on long-term schedule and short-term schedule, respectively. Section 4 introduces correlative optimized solution. The dispatch management of wind power risk is proposed in detail in Section 5.

2. Long-term economic dispatch model with wind power

When the ED including wind power considers the uncertainty nature of the wind power, the cost and reliability will be the main problem. Majority of objectives of optimization is to maximize the expected benefits or minimize the cost of system satisfying the system constraints at the same time, especially on long-term schedule.

2.1. The objective function involving cost

For keeping the reliability of the system, the factors for overestimation and underestimation of operator must be considered when solving the ED problem. When available wind energy is more than what is generated, power could be wasted. So it is necessary to pay the economic loss of the wind producer because of the surplus energy. In the other condition, the system operator underestimate the available wind energy, enough reverses are needed to make up the scarcity of power. As a result, the cost of reverses should be added to the objective function [1].

In [2], Hetzer et al. creates a new model, which adds wind energy conversion system (WECS) to the ED problem.

Objective function

$$F_T = \sum_i^M C_i(P_i) + \sum_i^N C_{wj}(w_i) + \sum_i^N C_{p,wj}(w_{i,av} - w_i) + \sum_i^N C_{r,w,i}(w_i - w_{i,av}) \quad (1)$$

Constraint

$$P_{i,\min} \le P_i \le P_{i,\max} \quad (2)$$

$$0 \le w_i \le w_{i,r} \quad (3)$$

$$\sum_i^M p_i + \sum_i^N w_i = L \quad (4)$$

Where the Weibull probability density function of the stochastic wind speed characteristic is used to transform wind distribution to the similar wind power distribution and compute the reverse cost.

Chen et al. considers the special contractual agreements for buying or selling energy between each independent power producer (IPP) and the public utility [3]. If the system producer owned the wind generators, the cost of wind power and penalty cost should be added in the function.

A trapeziform subjected function of objective function is contributed to calculate the pleasure degree of system operator [4]. In this way, the objective of the optimization is transformed from the minimization of operational cost to maximization of pleasure degree.

2.2. The bi-objective function incorporating risk level

In power market, minimizing the operational cost of differing generators and the risk level are two vital *objectives*. Because integrating the unpredictable and uncertainty characteristics of wind power into the traditional thermal generation systems will bring the problem of system security, which the operator concerns.

In [5–7], a bi-objective economic dispatch problem related with wind power penetration is described. In this model, it considers operational cost and security factors as opposite objectives which should be minimized simultaneously. They define a fuzzy membership function μ as the system security level, which can be described as two ways. In one side, the relationship between system security level and wind power penetration in ED can be linearization when the available wind power penetration is in the limit. In another side, a quadratic membership function is defined to reflect dispatcher's different attitude, which is a corporate tactical or strategic plan that views wind power penetration with a pessimistic or optimistic attitude. That is to say that the security level μ will alter with wind power penetration. At the same time, Wang et al. added the quadratic functions with sine components, which represent the rippling effects produced by the steam admission valve openings to the cost function of different generators, and utilize the function of the security level μ to reflect the running cost of wind power.

2.3. The objective function combining different types of wind farms in delegated dispatch

The delegated dispatch is a control centre, which monitors and controls the wind generation producers to transmit the requirements of the system operator in instant situations. It includes producers with different production controllability of the wind park, which must be analysed in function of their possibility to control its active and reactive outputs. But some older wind farms are less controllable. So the wind farms can be classified for three types based on their controllability [8], which are fully-control, partial-control and non-control.

According to this theory, Castronuovo et al. constitutes the dispatch model, which can be divided into three parts. Because of the existence of different types of wind farms, the goal of the model is not only to maximize the profit of wind farms, but also to decrease the quadratic difference between the active power and the maximum available instantaneous active power and to reduce the quadratic deviation between the power production angle of the wind parks and specified angles for this class of productions.

2.4. The objective function considering environmental damage cost

With the development of power technique, environmental problem has been attracting more and more people's attention. The most important environmental influence results from the wasting of the primary fuel and its conversion into electricity for the majority of fossil-fuel power generation. Kennedy presents a new method and a valuation model which includes energy, capacity, and environmental costs, and generation mix before installing wind power capacity to estimate the social benefit of large-scale wind power production in long schedule [9]. This paper mainly discusses the impacts related to plant operations, so output of displacing energy will produce an environmental benefit while displacing capacity will not. The advantage of this valuation model is to require a relatively small amount of data allowing for considerable flexibility integrating technologies.

3. Short-term economic dispatch model with wind power

For coping with discrete, large-scale, non-linear, and non-convex problem of short-term of economic dispatch with wind power, many accurate models which can conform to the theory of symmetrical fuzzy programming [10] are constituted to better dispose the characteristic of wind generation while maintaining or even enhancing the current stability and economic performance of power systems. Hong and Li explain the reason why the fuzzy wind models are effective and make simulation to prove it. Comparing with long-term schedule, short-term schedule should be taken into account of more precise constraints, e.g. time limits.

3.1. The objective function incorporating stochastic security

The stochastic security which can accounts for the expected costs of preventive security actions and post-disturbance corrective security actions is proposed as a way to further improve the systematic scheduling of reserves. Comparing with conservative deterministic approaches, stochastic security approach is according more with actual condition.

In [11], Bouffard and Galiana modeled the uncertain wind turbine generation (WTG) and load based on scenario approach considering scenario-specific unit commitment and ramping constraints. The aim of the electricity market-clearing problem is also to minimize a measure social cost, the model is as follows:

$$F_T = \sum_{i=1}^{M}[C_i(P_i) + C_r(r_i^{up}, r_i^{dn})] - \sum_{(k,l)\in T} p_i(k)[B_d(d_i(k)) - C_i(g_i(k)) - \nu_i^T l_i(k)] \quad (5)$$

This model utilizes the probability function of the expected social cost function to change the uncertainty of power system into mathematics formula. Only in this way can their associated sets of decisions variables be taken before the revelation of the uncertainty. So the concept of stochastic security is transformed into the style of probability.

3.2. The objective function combining energy storage in balancing market

Bathurst and Strbac introduces a simple algorithm [12] comparing with more advanced methods [13], which can compute the optimal dispatch of an electrical energy storage (EES) combining the short-term power exchange and the expected imbalance penalties of a wind farm. Based on the trait of the effect of daily price variation, imbalance price spread, market closure lead-times, and wind contracting errors, writer institutes the optimal EES dispatch algorithm and model with wind farm to increase the added value (AV) in tradeoff.

Garcia and Weisser create two models to decide the size of grid units and dispatch in a wind–diesel power system with hydrogen storage for reducing the cost [14]. One is linear programming, the other is heuristic policies. Through comparison, linear programming is viewed as a benchmark to improve heuristic dispatch rules. Though heuristic rule can deal with diversification of the wind seasonality, it cannot be accounted for wind stochastic. The result shows the complex relationship between unit sizing decisions and dispatch policies in the presence of storage.

3.3. The objective function considering spinning reserves

For solving the problem of system load forecast uncertainties, wind speed forecast uncertainties and balancing the system load, Siider proposes a new methodology [15] to establish the operation planning emphasizing on keeping of reserves which can be trisected for instantaneous, fast and slow reserves and establishes two models which are the wind power model and the conventional hydro-thermal model. One includes the forecast of total wind power generation and the uncertainty of the forecast, and the other extends to take into account load forecast uncertainty and reserve margins of the generation units. So it is more accurate and all-sided to make short-term dispatch plans of wind-hydro-thermal power systems through reckoning available capacities of the corresponding reserve type.

3.4. The objective function including start-up/shut-down cost

The economic dispatch including wind power is to find an optimal assignment style of different generators, so the cost of start-up and shut-down of generators should be a significant component of the total cost. Reducing the frequency of start-up and shut-down of generators is efficiency method to cut down the operational cost.

In [16], Chen proposed a linear model which consider additional up/down spinning reserve capacity and total actual wind power generation. Because wind power needs no fuel, the total cost of WTG from the public utility is the cheapest. Based on this theory, the writer decomposes operation cost into two parts: One is the system generation cost of the fuel expense for balancing the system load demand and reserves. Another is the start-up cost, which the unit operation trajectory controlled. A method for solving short-term scheduling considering start-up/shut-down cost is also proposed in [17,18]. On the side, the combination of the mixed integer linear objective function including operational costs, the turbine (on/off) status, start-up and shut-down of each turbine and the non-linear function of minimization of the mismatch between the total wind park generation output (active and reactive) and wind park dispatch center requests, are also brought forward in [19].

4. Optimized algorithm for dispatch model

With the development of traditional calculus and stochastic searching techniques consisting of direct search method (DSM), evolutionary programming (EP), genetic algorithm (GA), particle swarm optimization (PSO) and simulated annealing (SA), economic dispatch problem of power network with wind generators is further optimized in computing precision and convergence speed.

4.1. Direct search method

Direct search method is a local optimization heuristic method that purposes to maximize (or minimize) an unconstrained function using values only. Direct search methods do not claim global or local optimality of the computed solution but in many cases they can prove useful.

But this complex economic dispatch problem cannot apply DSM directly, so the writer decompounds the confused problem into wind and thermal sub-problems. To estimate the wind generation solution for initialization, a brief method [3] based on an equal incremental cost rule is used. After deciding total actual wind power generation, system spinning reserve capacity and the total operation cost of the WTG can also be reckoned. The sequential thermal sub-problem can be solved using the DSM algorithm in the standard reserve constrained economic dispatch. The most notable advantage of the DSM algorithm is beginning with an initial feasible solution and looking for the optimal solution along a trajectory, which can maintain a feasible solution that is the most notable advantage of the DSM algorithm.

4.2. Particle swarm optimization

Particle swarm optimization is one of the most recent developments in the category of evolutionary computational metaheuristic optimizations. This method has been developed based on the natural phenomenon of a bird flock or fish school. PSO is stochastic optimization technique. The individual in a population represents a particle. The position of each particle is called a potential solution to the target problem. The velocity of each particle represents the distance to be moved at the next step. The fitness of a particle is computed by objective function with former position. So the new velocity and the new position of each particle is updated after each iteration to adjust the variable for achieving the global best position These courses make a PSO system combine the local search methods with global search methods.

The classical PSO algorithm does not have the ability to solve multi-objective optimization problems because there is no absolute global optimum existing there. So Wang and Singh in [5] modify the PSO algorithm combing the nondominated pareto-optimal solutions in terms of the specified multiple design objectives, and utilize the multi-objective particle swarm optimization (MOPSO) to settle the problem of wind power dispatch with respect to risk and cost. Comparing with classic particle swarm optimization, i.e. MOPSO which has the ability to deal with constraints through a constraint checking procedure called rejecting strategy through creating archive and a candidate solution. Numerical simulations prove the validity and applicability of this approach.

4.3. Simulated annealing approach

Simulated annealing approach shows the process of annealing in physics in which a crystalline solid is heated and then very slowly cooled until it achieves its regular crystal lattice shape. The lowest energy state is to reach the aim of this process. If the cooling process is sufficiently slow, physical substances usually move from higher energy states to lower ones in this process. SA is widely utilized in structural optimization problems because of its inherent simplicity and ability to find the global optimum even if there are many design variables.

Chen writes the paper combining an effective constrained dynamic economic dispatch (CDED) method with the improved SA [16]. The SA algorithm with special random-perturbation scheme which can satisfy the most difficult minimum uptime and downtime constraints is used to optimize the generating unit schedule. And then the ramp-rate CDED is calculated by a direct search method. Through this improvement, the time-dependent constraints, such as ramp-rate constraints and wind generation fluctuation constraints, can be computed in the economic dispatch with wind power at the same time.

4.4. Genetic algorithm approach

Genetic algorithm approach is stochastic search arithmetic, which is based on natural selection in biology. Through successive selection, crossover, mutation and reproduction, GA can approach the global optimum and have the capability of dealing with problem including the inequality constraints efficiently.

Hong and Li consider the power generation with uncertainties which are modeled by a fuzzy set, and propose a genetic algorithm

approach to solve this problem which can computed as symmetrical fuzzy program [10]. Because feasible and infeasible regions compose the solution space for GA, the writers add the penalty functions in GA to reinforce the corresponding interferential constraints from the infeasible region into the feasible region to increase the computation speed. Through comparison with simulated annealing, this measure shows the steady convergence of iterations in a reasonable time.

4.5. Scenario construction method

Bouffard et al. constructed the scenario-based approach [11] to compute the unit commitment, reserve levels, HTG dispatches, negatively correlated WTG and load more explicitly on short-term schedule, and then utilize generation methods and the scenario modeling to approximate the value of WTG and load over the scheduling limit. In addition, because the stochastic approach includes the extra flexibility provided by coordinated involuntary load shedding and wind spillage actions, it permits the expansion of the feasible space of the security-constrained market-clearing problem. So scenario construction method can solve the issue of wind power dispatch satisfying stochastic security on short-term schedule.

5. Risk dispatch management of wind power in power market

Risk dispatch management, which attempts to obtain the total maximal of revenue or reduce the cost and risk of system aims to solve the uncertainty of wind speed in this paper. For security and stabilization of system, short-term forecast which is up to 48 h ahead of schedule are necessary. But because the information related with climatological and micrometeorological parameters are not extremely completed, wind speed is a non-stationary and non-linear resulting in a main trouble which the prediction intervals of cut-off speed can change from zero to maximum. [20,21]. So it is necessary to find an optimal risk management of the wind power production to enhance the robusticity of the whole system with wind power.

5.1. Management method in power market

As a result of the intrinsic stochastic characteristic of wind speed, which may bring on the disturbance of system, several measures in allusion to wind speed uncertainty are proposed in this paper.

Kariniotakis et al. utilize the time series method to transform the uncertainty wind speed to output of wind power [26]. Because stochastic nature and chronological changeability of the wind velocity determine the power output, there exists a non-linear relationship between the power generated by a wind turbine generators and the available wind speed. Though the historical mean wind speed u_t and its standard deviation σ_t, the simulated wind speed ν_t can be computed as followed:

$$\nu_t = u_t + \sigma_t y_t \qquad (6)$$

In this way wind speed can be estimated ahead. And then the power output can be calculated through establishing quadratic equation of wind speed based on the relationship with cut-in speed and cut-out speed. This method is effective when the orderliness of wind speed can be found.

A fuzzy approach [22] based on a multi-linearized fuzzy power flow is presented by Mangueira et al. to estimate uncertainties of the wind generation systems. For improving the quality of the linearization, the writers' models the assessment of the influence of wind power on the conventional electric grid as fuzzy numbers which include the last meteorological data, forecast accuracy data and wind generation operator data to reduce the uncertainty of the original problem. Through this measure, the system dispatcher and independent generator can evaluate the risk of contracts not-accomplishment even though wind power is quite small comparing with the total load.

Due to the wind speed trait mainly keeps to a Weibull distribution along with time changing at a given place [23]. Hetzer et al. utilize the Weibull distribution function, which has two parameters to compute the wind power probability function [1], because Weibull distribution function is more common than the single parameter Rayleigh distribution, and less complex than the five-parameter bivariate distribution. In [24], the evaluation of wind power uncertainty and its standard error are disposed with Weibull distribution in detail.

Salles et al. propose two methodologies which are Monte Carlo Simulation (MCS) and Bar and Jenkins (B&J) approach for wind power economic analysis considering uncertainties related with wind speed [25]. Integrated sequences of wind speeds and the wished value of financial indicators which can compute empirical probability distributions for financial risk analysis can be obtained by these two methodologies from a wind speed observed series.

Considering the wind speed forecast imprecision and weather instability, a generic method to evaluate short-term wind power forecast risk on-line is introduced [26,27]. For avoiding a restrained hypothesis on the distribution of the errors, confidence intervals with a confidence level including the prediction horizon, the cut-off risk and the power class are presented based on the resampling approach. This method is quite universal and can be applied to all kinds of wind forecasts to solve the problem of wind power uncertainties.

The uncertainties of wind power may break the normal transmission to load, so the special capacity of reverses is necessary. In [28], Doherty et al. point out another approach to estimate the reserve of the system with uncertain wind power. Considering the probability of load and generation being out, wind power and load forecast error, it is possible to create relationship between the reserve level on the system in each hour and the reliability of the system over the year to reckon value of reverse. In this way the capacity of reverses and security of system can be connected to make the power network with wind generator more robust.

6. Conclusion

The goal in this paper is giving a review on the economic dispatch problem and risk management of wind power in electricity market. Based on the different styles of schedule, the factors which the dispatch models consider are dissimilated. Except for the total fuel cost, models append factors of risk level, type of wind farms, spinning reserves, environmental damage cost, etc. For further improving constringency speed of computation, many optimized algorithms are combined with relevant model. Aiming at intermittency and unpredictability characteristic of wind power generation, this paper introduces several management methods to solve the wind power uncertainty problem to keep system stable and secure.

From these studies, we can conclude from the following three aspects:

- The wind power dispatch and risk management has much depended on the precision of speed forecast which may be meaningful if the historical wind speed has disciplinarian to follow at present, so it is still a difficult problem for ruleless wind speed.
- The more factors of wind dispatch are considered, the more complex the dispatch model is. So simplex optimized algorithms,

especially the intelligent algorithm cannot satisfy the demand of optimization, many studies are inclined to integrate the advantages of every algorithm and adopt the mixed algorithm to deal with different variables.

- The security and stabilization of the system are quite significant when integrating the wind power into the network, so the factors of risk management for wind power uncertainty should be further taken into account in dispatch model.

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